AN IONIZING UV BACKGROUND DOMINATED BY MASSIVE STARS

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ABSTRACT

We discuss the implications of a stellar-dominated UV background at high redshifts for the star formation history of Lyman-break galaxies (LBGs) and the thermal and ionization state of the intergalactic medium (IGM). The composite spectrum of 29 LBGs evaluated by Steidel et al. (2000) at $\langle z \rangle = 3.4$ can be well fit by a stellar population with ongoing star formation, a Salpeter initial mass function, modest or negligible dust reddening, and no intrinsic H I photoelectric absorption. Fading starbursts in which star formation has ceased for 10^7 yr or more cannot reproduce the observed flux shortward of 1 Ryd. The small H I optical depth in LBGs suggests that the neutral gas from which stars form is most likely contained in compact clouds of neutral gas with small covering factor. The escape fraction of H-ionizing photons must be close to 100 percent for the observed sample of LBGs. The spectrum of ionizing photons produced by a stellar population with ongoing star formation is similar to that of QSOs between 1 and 3 Ryd, but becomes softer between 3 and 4 Ryd and drops sharply shortward of 4 Ryd. A galaxy-dominated UV background appears inconsistent with the observed He II /H I opacity ratio at $z = 2.4$, but might be able to explain the Si IV/C IV abundances measured at $z > 3$ in quasar absorption spectra. A scenario may be emerging where star-forming galaxies reionized intergalactic hydrogen at $z > 6$ and dominate the 1 Ryd metagalactic flux at $z > 3$, with quasi-stellar sources taking over at lower redshifts. If the large amplitude of the H-ionizing flux estimated by Steidel et al. is correct, hydrodynamical simulations of structure formation in the IGM within the cold dark matter paradigm require a baryon density (to explain the observed opacity of the Lyα forest in quasar absorption spectra) which is similar to or larger than that favoured by recent CMB experiments, and is inconsistent with standard nucleosynthesis values.

Subject headings: cosmology: theory — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The strength and spectrum of the UV ionizing background at high redshift and the nature of the sources which reionized the hydrogen component of the intergalactic medium (IGM) are two of the big outstanding questions in observational cosmology. QSOs and star-forming galaxies have long been considered the two prime candidates. It has been argued that QSOs may fall short of producing a metagalactic flux as high as that inferred from the proximity effect at high redshift (Bechtold 1994; Giallongo et al. 1996; Cooke et al. 1997; Scott et al. 2000) since their space density declines rapidly at early epochs (Shapiro & Giroux 1987; Miralda-Escudé & Ostriker 1990; Meiksin & Madau 1993; Madau et al. 1999). The detection of a numerous population of Lyman-break galaxies (LBGs) at $z \approx 3$ (Steidel et al. 1996) makes the idea of massive stars dominating the UV background at early epochs quite plausible. At 1500 Å their emissivity outweighs that of QSOs by about a factor of fifteen (Madau et al. 1999). Until recently it seemed likely that only a small fraction of the ionizing photons emitted within starburst galaxies could escape the dense H I layers into the IGM, as is observed in their low-redshift counterparts (Leitherer et al. 1995; Hurwitz et al. 1997). The detection by Steidel et al. (2000) of flux beyond the Lyman limit (with no significant indication of a break at 912 Å) in a composite spectrum of 29 LBGs at $\langle z \rangle = 3.4$ thus comes as a surprise.

In this *Letter* we assess the significance of the Steidel et al. (2000) findings by comparing their spectrum to model spectra calculated with the population synthesis code STARBURST99 (Leitherer et al. 1999). We discuss the implications of this result for the star formation history and gas content of these galaxies, for the spectrum of the UV background, for the cosmological reionization, and for the baryon content of the Universe.

2. IMPLICATIONS FOR THE STAR FORMATION HISTORY

The most striking feature of the composite spectrum of Steidel et al. is the apparent lack of a significant drop at the Lyman limit. Stars with effective temperatures $\lesssim 30,000$ K have a strong intrinsic break at the Lyman edge. The composite spectrum shortwards of 1 Ryd is thus dominated by O stars with masses $\gtrsim 20 M_\odot$ and lifetimes $\lesssim 10^7$ yr. Note that the signatures of O stars have already

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been detected at longer wavelengths (Pettini et al. 2000) so their presence does not come as a surprise. Considering the large space density and luminosities of LBGs (Steidel et al. 1996) it seems very unlikely that these galaxies have been caught during a very short starburst. In Fig. 1 we compare the observed spectrum with a model spectrum calculated with the population synthesis code STARBURST99 (Leitherer et al. 1999). We have assumed a constant rate of star formation lasting for $t_* = 10^8$ yr, a Salpeter initial mass function (IMF) from 1 to 100 $M_\odot$, and solar metallicity. The spectrum is dominated by stars in the mass range $15 - 60\,M_\odot$, and has been convolved with the model of the opacity distribution of the Lyα forest clouds and Lyman-limit systems of Madau (1995). To improve the fit to the data a modest amount of reddening was introduced, $E_{B-V} = 0.03$ for a SMC (absorption only, no scattering) extinction curve (Pei 1992).

The agreement between the model spectrum and the data is rather good, although the observed flux shortward of 1 Ryd appears somewhat higher than in the model. The discrepancy is, however, within the uncertainties in the spectral synthesis and intergalacitc opacity modeling. For comparison, we also show the spectrum of an instantaneous starburst after 10^7 yr. This has basically no flux shortward of 1 Ryd. Fading starbursts with short duty cycles may thus be problematic (e.g. Kolatt et al. 1999). Note that there is no hint of a significant H I photoelectric optical depth in the local interstellar medium (ISM).

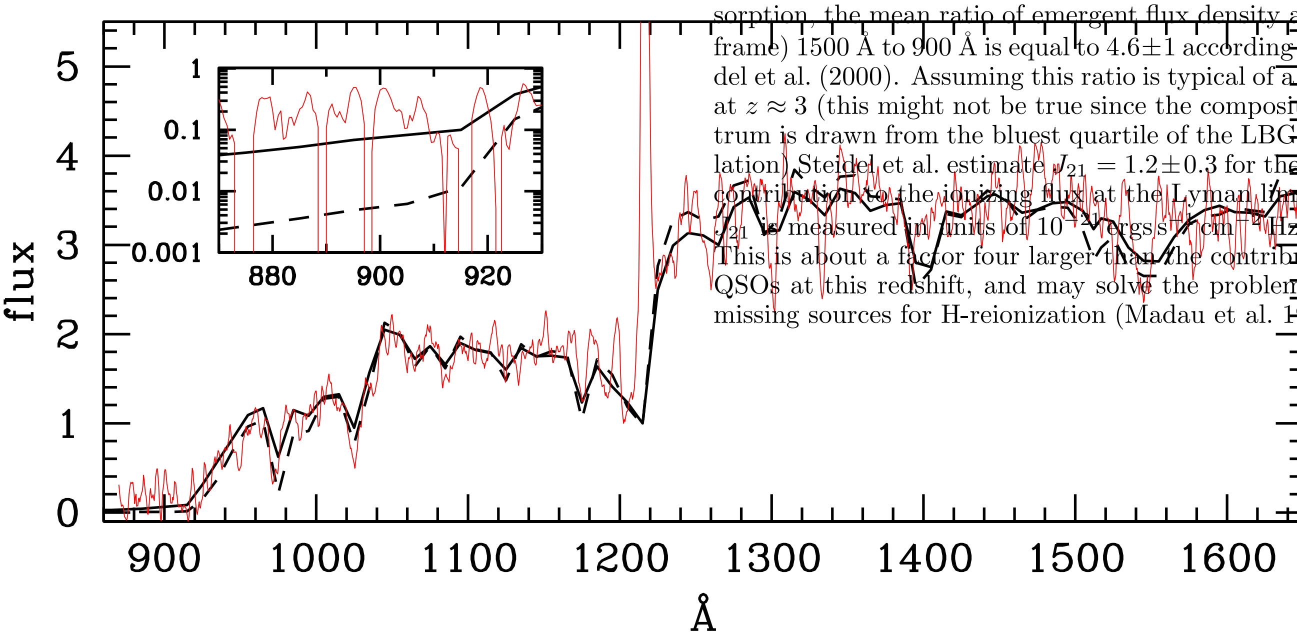

Fig. 1.— *Thin solid curve:* composite spectrum of 29 LBGs at $\langle z \rangle = 3.4$ from Steidel et al. (2000). *Thick solid curve:* synthetic spectrum of a stellar population with continuous star formation and Salpeter IMF. A modest amoung of reddening with a SMC extinction curve and $E_{B-V} = 0.03$ was included. *Dashed curve:* synthetic spectrum of an instantaneous starburst after 10^7 yr. The model spectra were calculated with STARBURST99 (Leitherer et al. 1999).

3. THE NEUTRAL HYDROGEN DISTRIBUTION AND ESCAPE FRACTION OF LYMAN-BREAK GALAXIES.

If star formation in Lyman-break galaxies is indeed continuous and lasts for about a hundred Myr there should be a substantial amount of neutral hydrogen present in these systems. The LBGs in Steidel et al. sample have typical star formation rates of $\dot{M}_* = 10 - 50\,M_\odot\,\mathrm{yr}^{-1}$. They should thus contain $M \approx 10^{9.5} (30\,M_\odot\,\mathrm{yr}^{-1}/\dot{M}_*)\ (t_*/10^8\,\mathrm{yr})\,M_\odot$ of cold gas if the cold gas to stellar mass ratio were of order unity. Taking a typical half-light radius of 2 kpc as characteristic size and assuming that the cold gas is distributed homogeneously, the typical density and column density should be $\sim 3\,(M/10^{9.5}M_\odot)\,(r/2\,\mathrm{kpc})^{-3}\ \mathrm{cm}^{-3}$ and $2 \times 10^{22} (M/10^{9.5}M_\odot)(r/2\,\mathrm{kpc})^{-2}\,\mathrm{cm}^{-2}$, respectively. These values are higher than those of damped Lyα systems and a large H I optical depth would therefore be expected.

A luminosity in ionizing photons of at least $\sim 10^{44.5} (M/10^{9.5}M_\odot)(r/2\,\mathrm{kpc})^{-3}\,\mathrm{ergs\,s^{-1}}$ is needed to keep this large amount of gas photoionized. The required luminosity is a factor $10 - 30$ higher than that of the LBGs in the sample. Lyman-break galaxies should therefore either have a small cold/neutral gas mass to stellar mass ratio in their luminous regions or the cold gas must be contained in small compact regions with small covering factor.

4. THE UV ESCAPE FRACTION OF GALAXIES AND THE REDSHIFT EVOLUTION OF THE UV BACKGROUND

The absence of a significant intrinsic H I photoelectric opacity in the spectra of LBGs implies that those ionizing photons which avoid absorption by dust can escape the galaxy unimpeded. After correction for intergalactic absorption, the mean ratio of emergent flux density at (rest-frame) 1500 Å to 900 Å is equal to 4.6 ± 1 according to Steidel et al. (2000). Assuming this ratio is typical of all LBGs at $z \approx 3$ (this might not be true since the composite spectrum is drawn from the bluest quartile of the LBGs population) Steidel et al. estimate $J_{21} = 1.2 \pm 0.3$ for the galaxy contribution to the ionizing flux at the Lyman limit (here J_{21} is measured in units of $10^{-21}\,\mathrm{ergs\,s^{-1}\,cm^{-2}\,Hz^{-1}\,sr^{-1}}$). This is about a factor four larger than the contribution of QSOs at this redshift, and may solve the problem of the missing sources for H-reionization (Madau et al. 1999).

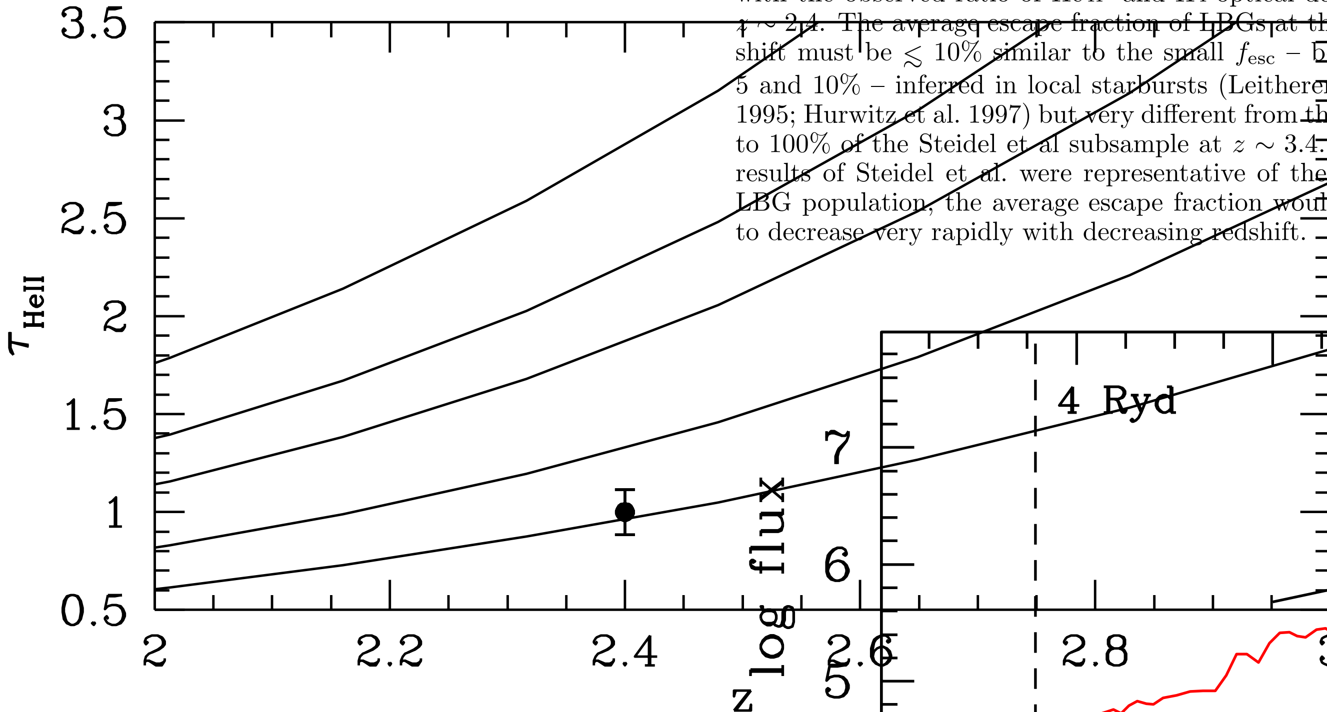

Fig. 2.— The He II line blanketing opacity as a function of redshift for a UV background dominated by QSOs and stars. The different curves show the optical depth for a stellar contribution to the flux at 1 Ryd equal to (0, 0.5, 1.5, 2.5 and 5) times that of QSOs (from bottom to top). The H I optical depth is fixed to $\tau_{\rm HI} = 0.0038\,(1+z)^{3.46}$, while the ionizing flux at $z = 2.4$ from QSOs *only* is $J_{21} = 0.3$ in all cases (Haardt & Madau 1996). The curves correspond to an escape fraction of Lyman-continuum photons from star-forming galaxies of (0, 10, 30, 50 and 100) percent. The data point is from Davidsen et al. (1996).

Could the UV background be dominated by stars at all redshifts? Comparison of both H I and He II absorption in quasar spectra can be used to constrain the relative contribution of massive stars and QSOs to the metagalactic flux. While in three out of four of the observed QSO spectra with a He II Lyα forest the interpretation is made difficult by the large fluctuations measured in the He II scattering opacity – perhaps the signature of a delayed He II $\rightarrow$ He III reionization at $z \gtrsim 3$ – (see, e.g., Reimers et al. 1997; Heap et al. 2000) the spectrum of HS1700+64 at somewhat lower redshifts ($2.4 < z < 2.7$; Davidsen et al. 1996) shows smaller fluctuations and allows a more reliable determination of the average He II optical depth, $\overline{\tau}_{\rm HeII} = 1.0 \pm 0.07$. This value is in good agreement with that expected for a quasar-dominated ionizing background filtered by the IGM (Haardt & Madau 1996) with a frequency dependence of the intrinsic quasar spectrum, $f_\nu \propto \nu^{-1.8}$ (Machacek et al. 2000; Theuns et al. 1998; Croft et al. 1997). In Fig. 2 we show the He II line blanketing optical depth for a UV background with different ratios of QSO and galaxy contribution, for a given H I scattering opacity. The five curves correspond to an escape fraction of H-ionizing photons from galaxies of (0, 10, 30, 50, 100) percent (bottom to top). For fixed H I scattering opacity the He II optical depth increases with increasing stellar contribution to the total flux.

A UV background dominated by stars is inconsistent with the observed ratio of He II and H I optical depth at $z \sim 2.4$. The average escape fraction of LBGs at this redshift must be $\lesssim 10\%$ similar to the small $f_{\rm esc}$ – between 5 and 10% – inferred in local starbursts (Leitherer et al. 1995; Hurwitz et al. 1997) but very different from the close to 100% of the Steidel et al subsample at $z \sim 3.4$. If the results of Steidel et al. were representative of the entire LBG population, the average escape fraction would have to decrease very rapidly with decreasing redshift.

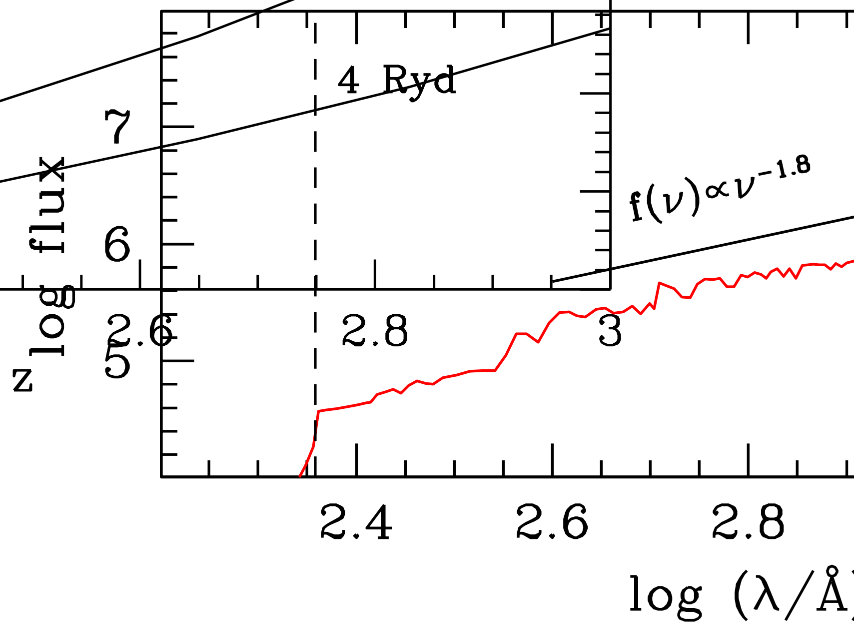

Fig. 3.— Extrapolated far-UV synthetic spectrum of a stellar population with continuous star formation. A SMC reddening curve as modeled by Pei (1992) and the dust opacity distribution of LBGs as given by Steidel et al. (1999) have been assumed. The line indicates the slope of a typical QSO spectrum with $f_\nu \propto \nu^{-1.8}$.

5. A UV BACKGROUND DOMINATED BY STELLAR SOURCES AT HIGH REDSHIFT

Having found a simple model which reproduces the observed spectrum in the wavelength range 870 Å to 1600 Å we can now extrapolate the UV spectrum to shorter wavelength. The result is shown in Fig. 3. We have assumed the full range of dust optical depth as reported by Steidel et al. (1999) with no dependence of dust optical depth on galaxy luminosity, together with a SMC reddening curve (absorption only, no scattering; Pei 1992). We also assumed that the null detection of H I absorption due to the ISM in the Steidel et al. sample is representative of all LBGs. Just beyond the Lyman limit the spectrum is very similar to that of a typical QSO, somewhat harder than the canonical -1.8 power law (Zheng et al. 1998). It is only at wavelengths shorter than 400 Å that it softens significantly compared to a quasar spectrum. Beyond the He II Lyman edge at 4 Ryd there is a strong break.

The similarity to a QSO spectrum just beyond 1 Ryd may explain the already high temperatures of 10^4 K at $z > 3$ (Haehnelt & Steinmetz 1998; Schaye et al. 2000). A UV background which is progressively dominated by O stars may also be the solution to the increasing Si IV/C IV ratio with increasing redshift observed in metal absorption systems of intermediate column densities (Songaila & Cowie 1996; Giroux & Shull 1997; Boksenberg et al. 1998).

How different could the integrated stellar spectrum be? The upper cut-off of the IMF and the metallicity will strongly affect how far the spectrum extends into the far UV (Tumlinson & Shull 2000; Bromm et al. 2000; Oh et al. 2000). We have assumed an upper cut-off of $100 M_\odot$ and solar metallicity. The dust opacity in the far UV depends on smaller grains than usually probed by reddening analysises and is rather uncertain. In the the model of Pei et al. (1992) for the SMC opacity used here, the dust opacity drops shortwards of 1000 Å. This makes the spectrum bluer not redder at wavelengths shorter than 1000 Å. The stellar spectrum of massive stars with strong mass loss are complex and require non-LTE calculations including the effect of stellar wind outflow and spherical extension. In particular, the strength of the 4 Ryd break depends significantly on metallicity, mass loss rates and details of the modelling (Kudritzki 2000; Pauldrach et al. 2000).

6. THE BARYON FRACTION OF THE UNIVERSE

One interesting consequence of the large amplitude of the UV background suggested by Steidel et al. is the implied conflict of the Lyα opacity measurements in QSO spectra with the nucleosynthesis constraint for the baryon density. The optical depth for Lyα scattering of the photoionized IGM scales as (Rauch et al. 1997a) $\tau_{\mathrm{Ly}\alpha} \propto H(z)^{-1}(\Omega_{\mathrm{b}} h^2)^2 T^{-0.7}\Gamma^{-1}$, where Γ is the photoionization rate, T is the gas temperature, $H(z)$ is the Hubble constant at redshift z, Ω_{b} is the baryon density parameter, and h is the present-day Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The investigation of Rauch et al. implies that for a nucleosynthetic value of $\Omega_{\mathrm{b}} h^2 = 0.019$ (Burles & Tytler 1998) the Lyα opacity can be matched if $\Gamma \sim 5\times10^{-13}\,\mathrm{s^{-1}}$. For a spectrum $f_\nu \propto \nu^{-1.8}$ this corresponds to an ionizing flux $J_{21} = 0.12$. The large value of $J_{21} = 1.2 \pm 0.3$ suggested by Steidel et al. implies instead $\Omega_{\mathrm{b}} h^2 \approx 0.06$. The D/H measurements are therefore in strong conflict with the Lyα opacity measurements if both the standard nucleosynthesis calculations and the value of J_{21} suggested by Steidel et al. are correct. This discrepancy may be even stronger if there were a significant contribution to the H-ionizing background from faint Lyα emitters with weak stellar continuum flux as suggested by Kudritzki et al. (2000).

In Fig. 4 we have compiled from the literature a number of values for $\Omega_{\mathrm{b}} h^2$ implied by the measured Lyα opacity assuming $J_{21} = 0.6$ as may be appropriate if LBGs with redder spectra than those in the Steidel et al. sample had significant smaller escape fraction for H-ionizing photons. The values at $z = 3$ are taken from Rauch et al. (1997b), Gnedin (1998), Nusser & Haehnelt (2000), Theuns et al. (2000), and at $z = 2$ from Cen et al. (1994) and Hernquist et al. (1996). We have scaled all values to a temperature of 15000 K at $z = 3$ and 11000 K at $z = 2$ as suggested by the temperature determination of the IGM by Schaye et al. (2000). All values for Ω_{b} scale $\propto J_{21}^{0.5}$ and $\propto T^{0.35}$. We also show the nucleosynthesis constraint from the D/H measurement as given by Burles & Tytler (1998) and the combined constraints from the CMB experiments BOOMERANG and MAXIMA (Jaffe et al. 2000).

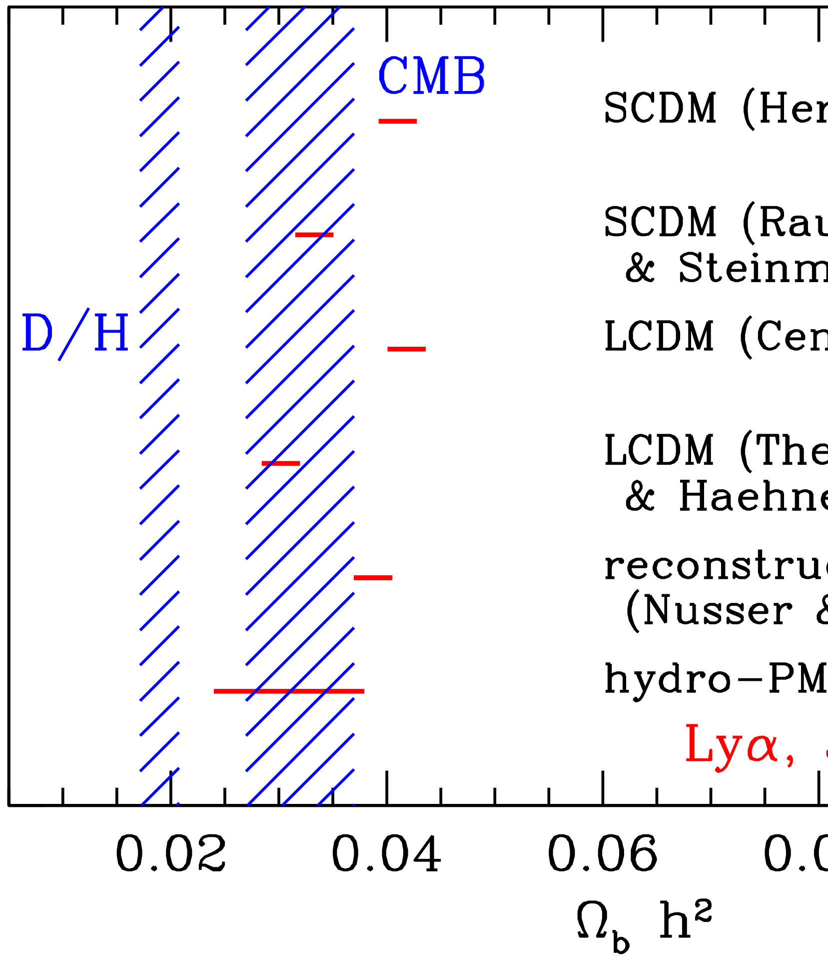

Fig. 4.— The baryon fraction inferred from the Lyα opacity as described in the text. The values inferred from D/H measurements (Burles & Tytler 1998) and CMB experiments (Jaffe et al. 2000) are also shown.

7. DISCUSSION AND CONCLUSIONS

We have shown that the detection of flux beyond the Lyman limit from LBGs is most easily explained as being due to the O stars present in a star forming region with ongoing star formation, a Salpeter IMF, modest or negligible reddening, and negligible absorption due to H I in the local ISM. Fading starbursts in which star formation has ceased for 10^7 yr or more cannot reproduce the observed flux shortward of 1 Ryd. The small H I optical depth cannot be due to photoionization. The cold neutral gas from which they stars form must be contained in compact small regions with small covering factor.

The resulting ionizing background will be dominated by O stars shortward of the Lyman limit and is as hard as a QSO spectrum between 1 and 3 Ryd. Shortward of 3 Ryd the spectrum is softer than a QSO spectrum and there is strong drop shortward of 4 Ryd. A consistent picture seems to emerge where the hydrogen of the Universe is reionized by stars at $z > 6$ while the reionization of helium is due to QSOs and is delayed to $z \sim 4$ or 3. The contribution of stars to the ionizing UV background is equal or larger than that QSOs at least up to $z \sim 3$. At smaller redshift the ratio of He II and H I opacity and the observed Si IV/C IV ratios in the associated metal absorption systems of intermediate column density QSO absorption systems argue for a UV background dominated by QSOs. This requires a substantial decrease of the escape fraction of ionizing photons from star-forming galaxies with decreasing redshift. The amplitude of the UV background inferred from the composite spectrum of Steidel et al. makes the measurements of the opacity of the Lyα forest in QSO absorption spectra inconsistent with D/H measurements if the spectrum is representative for all LBGs and nucleosynthesis calculations for D/H are correct. The inferred value for $\Omega_{\rm b}$ is similar to that that indicated by the CMB experiments Boomerang and Maxima if $J_{21} = 0.4 - 0.6$.

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